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Land Surface Temperature Measurements from EOS MODIS Data

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Abstract

The SIBRE (Spectral Infrared Bidirectional Reflectance and Emissivity) system and integrating sphere TIR system are being used to establish our TIR BRDF/emissivity knowledge base of terrestrial materials. The SIBRE system was also successfully used in a field campaign in Railroad Valley, Nevada, on August 3rd, 1995, with concurrent overpasses by MAS (MODIS Airborne Simulator) and TIMS (Thermal Imaging Multispectral Spectrometer). Field measurement data of surface emissivity and temperature, and MAS data are used to validate the generalized split-window LST (Land-Surface Temperature) algorithm. LST retrieved from MAS data using the generalized split-window LST algorithm agrees with field measurement LST values within 1°K. Beta-3 version of the MODIS LST code based on the split-window algorithm was delivered to the MODIS Science Data Support Team. We have developed a new LST algorithm for simultaneously retrieving surface band-averaged emissivities and temperature from day/night pairs of MODIS TIR data. This new method was tested with simulated MODIS data for 80 sets of band-averaged emissivities calculated from published spectral data for MODIS thermal bands in wide ranges of atmospheric and surface temperature conditions. Comprehensive sensitivity and error analysis has been made to evaluate the performance of the new LST algorithm and its dependence on the ranges of the atmospheric and surface conditions, and on the noise-equivalent temperature difference (NEAT) and calibration accuracy specifications of the MODIS instrument. In cases with systematical calibration errors of 0.5%, the standard deviations of retrieved surface daytime and nighttime temperatures, and band-averaged emissivities in MODIS bands 31 and 32 are in ranges of 0.2-0.7°K and 0.006-0.015 over a wide range of surface temperatures in summer mid-latitude atmospheric conditions.

1. Progress in Establishment of BRDF/Emissivity Knowledge Base

A spectral BRDF (bidirectional reflectance distribution function) and emissivity knowledge base is needed in use of the generalized split-window LST algorithm [Wan and Dozier, 1995]. Our spectral infrared bidirectional reflectance and emissivity (SIBRE) system and integrating sphere TIR system are being used for measurements of BRDF and emissivity of Earth surface material samples in the laboratory and in the field. Measured samples include soils, sands, and some vegetations. A special care has been taken to correct the effect of sample heating due to the thermal source irradiance [Snyder and Wan, 1996].

2. Validation of the Split-window LST Algorithm

We conducted a joint field campaign with the JPL ASTER team at a flat test site in Railroad Valley, Nevada, on August 3rd, 1995. The size of the test site is larger than 5km by 5km. MAS and TIMS data, and field measurement data of surface spectral emissivity and temperature with TIR spectrometer and broadband radiometer were collected. Spectral BRDF and emissivity of samples taken from the test site were measured with the SIBRE and the integrating sphere system. Once emissivity is determined, LST can be retrieved from MAS data by using our generalized split-window LST algorithm. The MAS data were calibrated with the new method [King et al., 1995]. Temporal surface temperatures are also retrieved from the field measurement spectral data of surface-leaving radiance and atmospheric downward radiation collected by our FTIR spectrometer at the test site. As shown in Table 1, LST retrieved from MAS data using the generalized split-window LST algorithm agrees with field measurement LST values within 1°C. This is mainly limited by the standard deviation of the spatial variation in LST around our field measurement point at scale of one MAS pixel to 1 km scale, as indicated by LST values retrieved from MAS data.

3. Beta-3 Delivery of the MODIS LST Code

The beta-3 version of the MODIS level-2 LST code based on the generalized split-window LST algorithm has been developed and tested with simulated MODIS data provided by MODIS SDST (Science Data Support Team). Level 2G LST code has been also developed under helps of SDST. These codes were delivered to SDST for software testing and integrating.

4. Development of New MODIS LST Algorithms

The generalized split-window LST algorithm is an easy and efficient method to retrieve land-surface temperature. It can retrieve LST at accuracy of about 1°K if we know the band-averaged emissivities of MODIS bands 31 and 32 within better than 0.01. But it is only possible to have such knowledge of the emissivities for certain types of land covers, such as lakes surfaces, snow/ice covers, dense evergreen canopies, and some soils. For land covers with variable emissivities, especially in semi arid and arid areas, it is impossible to estimate these two band-averaged emissivities to such accuracy, so it is necessary to develop new LST algorithms to retrieve LST without knowledge of surface emissivities.

4.1. Theoretical Basis of the New LST Algorithm

Due to the emissivity effect on thermal infrared signature received by satellite sensors we have to develop a new method that retrieves surface emissivity and temperature simultaneously. As well known, it is an under-determined problem to retrieve band-averaged emissivities and surface temperature from N thermal infrared channels even when atmospheric temperature and humidity profiles are known. Therefore, we turn to consider use of multi-temporal and multi-channel data. Li and Becker [1993] proposed a method to estimate both land-surface emissivity and LST using pairs of day/night co-registered AVHRR images. They use a temperature-independent spectral index in thermal infrared bands and assume knowledge of surface TIR BRDF and atmospheric profiles. MODIS is an unique instrument that has 3 channels in the medium infrared range 3.5-4.2µm. These 3 channels can be better used for correcting the solar effect in retrieving surface temperature. MODIS also has more channels in the spectral range 8-14µm so that it is possible to develop a physical based algorithm to retrieve surface band emissivities and temperature from MODIS TIR bands.

In general, the spectral infrared radiance at the top of the atmosphere is composed of surface thermal emittance, thermal path radiance, path radiance resulting from scattering of solar radiation, solar beam and solar diffuse radiation and atmospheric thermal radiation reflected by the surface,

$$L(\lambda, \mu) = t_1(\lambda)\, \varepsilon(\lambda, \mu)\, B(\lambda, T_s) + L_a(\lambda, \mu) + L_s(\lambda, \mu) + t_2(\lambda) \frac{\mu_0 E_0(\lambda)}{\pi} f_r(\mu; \mu_0, \phi) +$$

$$\int_0^{2\pi} \int_0^1 \mu' f_r(\mu; \mu', \phi') \left[t_3(\lambda, \mu) L_d(\lambda, -\mu', \phi') + t_4(\lambda, \mu) L_t(\lambda, -\mu', \phi') \right] d\mu' d\phi' , \qquad (1)$$

where μ is cosine of the viewing zenith angle, $E_o(\lambda)$ is the solar irradiance value on the top of atmosphere, μ_0 is from solar zenith angle, ϕ_0 is the relative azimuth between viewing direction and the solar beam direction. $f_r(\,)$ is the BRDF function, $L_d(\lambda, -\mu', \phi')$ is downward solar diffuse radiance, $L_t(\lambda, -\mu', \phi')$ is atmospheric downward thermal radiance, their incident direction is represented by $-\mu'$ and ϕ'. And t_i, $i = 1, 4$ are transmission functions for the corresponding terms. It requires complete calculations of the atmospheric radiative transfer to determine values of these terms in this equation.

In order to make practical use of multi-temporal and multi-channel data, we need to simplify the above equation by using some realistic assumptions about the surface optical properties. After considering related factors, we assume: 1) The surface emissivity changes with vegetation coverage and surface moisture content, but it does not significantly change in several days unless rain and/or snow occurs during the short period of time; 2) We have observed quite strong spectral variations in surface reflectance for some terrestrial materials but not in their TIR BRDF factor (the ratio between BRDF function and surface reflectivity) in the medium wavelength range (3.5-4.2µm), so it seems appropriate to assume that a single BRDF factor can be used for the surface reflected solar beam term in MODIS bands 20, 22 and 23 located in this wavelength range although this BRDF factor depends on surface structure and optical properties, solar zenith angle, and viewing angle; 3) Because in clear-sky conditions the surface reflected diffuse solar irradiance term is much smaller than the surface reflected solar beam term in the thermal infrared range, and the surface reflected atmospheric downward thermal irradiance term is smaller than surface thermal emittance, the lambertian approximation of the surface reflectivity does not introduce a significant error in thermal infrared region 3-14 µm.

Based on these assumptions, Wan and Li have developed the following physical based day/night LST model in their recent collaboration. The radiance measured in MODIS band j can be expressed as

$$L(j) = t(j)\,\varepsilon(j)\,B_j(T_s) + L_a(j) + L_s(j) + [1-\varepsilon(j)]\,[E_d(j) + f \times E_s(j)] \quad . \tag{2}$$

where *t(j)* , *j* = 1, 7, is the band effective transmission coefficient, ε *(j)* the band-averaged emissivity, $B_j(T_s)$ band-averaged Planck function which depends on surface temperature *Ts, La* the atmospheric thermal path radiance, *Ls* path radiance resulting from scattering of solar radiation, *Ed* the contribution from atmospheric downward thermal irradiance and solar irradiance reflected by a perfect reflecting surface, *Es* the contribution from the solar beam reflected by a perfect reflecting surface, and f is the BRDF factor for solar beam at viewing angle of the MODIS sensor. Note that π and transmission functions have been incorporated into *Ed* and *Es.* On the right hand of this equation, ε *(j)* and *Bj(Ts)* depend on surface properties and conditions, all other terms depend on atmospheric column water vapor and temperature (especially the atmospheric temperature T_a in the boundary layer near surface), solar angle and viewing angle. Theses can be given by numerical simulations of atmospheric radiative transfer. The spectral response functions measured from the Engineering Model of the MODIS instrument have been used as weights in calculations of band averages of these terms. For example, the band-averaged emissivity is

$$\varepsilon(j) = \frac{\int_{\lambda(j,lower)}^{\lambda(j,upper)} \Psi(\lambda)\,\varepsilon(\lambda)\,d\lambda}{\int_{\lambda(j,lower)}^{\lambda(j,upper)} \Psi(\lambda)\,d\lambda} \tag{3}$$

where Ψ(λ) is the spectral response function of band j, λ *(j,lower)* and λ *(j,upper)* are its lower and upper boundaries.

The 7 bands used in the new LST method are MODIS bands 20, 22, 23, 29, 31, 32 and 33. The specifications of these 7 bands are given in Table 2. According to the experience from the Engineering Model of the MODIS instrument, the NEAT in band 33 may be reduced from 0.25°K to 0.12°K, and it appears possible to achieve the goal for absolute calibration accuracy, 0.5-0.7570, for these 7 infrared bands. If we use daytime and nighttime data of these 7 bands, we have 14 observations. They are just enough to be used to solve the following 14 knowns: 7 band-averaged emissivities plus daytime surface temperature $T_{s\text{-}day}$, nighttime surface temperature $T_{s-night}$, daytime atmospheric temperature and column water vapor, nighttime atmospheric temperature and column water vapor, and the BRDF factor.

4.2. Radiative Transfer Simulations in Development of the New LST Algorithm

We will use the following scheme to simulate the variations of the atmospheric conditions in summer mid-latitude as an example: 1) To add to the average atmospheric temperature profile at all levels between surface and altitude 9km, varies from -10°K to +10°K in step 2 °K. We use the resulting atmospheric temperature at surface level as a variable parameter for the whole atmospheric temperature profile. 2) To scale the average atmospheric water vapor density profile at all levels in step 10% so that its lower limit will be 10% of the average and its upper limit will be 120% of the average.

We use the most recent version of MODTRAN3 code [Berk et al., 1989] to calculate all terms in Eq. 2 for each atmospheric condition at given solar angle and viewing angle. We used the discrete ordinate option with 8 streams in MODTRAN3 calculations so that multiple scattering is included. Based on this series of numerical simulations of atmospheric radiative transfer, we can build look-up tables for the atmospheric terms in Eq. 2 after making band averages with the spectral response functions. Similarly, a look-up table is also built for the band-averaged Planck functions.

4.3. Ranges of Land-Surface Emissivities and Temperatures

Band emissivities averaged with the MODIS spectral response functions as weights are calculated from published spectral reflectance data of 80 pure terrestrial materials [Salisbury and D'Aria, 1992], including igneous, metamorphic, and sedimentary rocks, varnished rock surfaces, lichen-covered sandstone, soil samples, green foliage, senescent foliage, ice, and water surfaces with suspended quartz sediment and oil slicks. As shown in Fig. 1, the band emissivity in MODIS band 20 could be as low as 0.55. However, the band emissivities in the last 3 bands are larger than 0.8.

In our simulations, the daytime surface temperature will be allowed to change in the range from atmospheric surface temperature T_{a-day} to T_{a_day} + 24°K in step 6 °K, and the nighttime surface temperature varies from $T_{a\text{-}night}$ – 13.5°K to $T_{a\text{-}night}$ + 4.5°K in step 4.5°K.

4.4. Numerical Method for Solving the Nonlinear Inversion Problem

We used the Quasi-Newton method [Dennis and Schnabel, 1983] and the Least-Squares Fit method [Bevington, 1969] to solve the set of 14 nonlinear equations in form of Eq. 2 for retrieving surface band-averaged emissivities and temperatures. The initial values of the 14 known variables are given in their constrained ranges based on reasonable guesses. The Quasi-Newton method is more computational efficient. These two methods give similar results in cases without including noises. As well known, global convergence to right solutions is not guaranteed for nonlinear problems, especially in cases with including noises. The Least-Squares Fit method is selected in the new LST algorithm because it is more stable in general cases. We are only interested in practical situations where noises at some realistic levels always exist in real remote sensing data.

4.5. Sensitivity and Error Analysis of the New LST Algorithm

Using these look-up tables, we can quickly construct 14 band radiance values (7 values for daytime and other 7 values for nighttime) at the top of the atmosphere for any given surface band emissivities and BRDF factor, daytime and nighttime surface temperatures, daytime and nighttime atmospheric surface temperatures and column water vapor values, solar angle and viewing angle. Then we can use these 14 radiance values as simulated MODIS observations to retrieve the given surface and atmospheric variables with the least-squares fit method. In the first example, we do not include any noise in the data construction in order to test the numerical method to solve the nonlinear problem and to evaluate the errors due to using look-up tables and interpolation methods. We set the daytime and nighttime atmospheric surface temperatures at 298.2°K and 290.2°K, column water vapor 2.6cm for both daytime and nighttime, BRDF factor as 2, solar zenith angle at 45°, viewing angle at nadir for daytime and nighttime, 5 different daytime surface temperatures ranging from 298.2°K to 322.2°K, and 5 different nighttime surface temperatures ranging from 276.7 ‘K to 294.7 “K. There are 25 cases of different daytime and nighttime surface temperatures for each sample in 80 surface materials. For most surface samples, the standard deviations of the retrieved surface temperatures are smaller than 0.1°K, the standard deviations of the retrieved emissivities are 0.002 for bands 1 to 6, 0.02 for the last band because of the low transmission of MODIS band 33 in the atmospheric condition. These numbers indicate that look-up tables are appropriate and the least-squares fit method works well.

In the second example, we set the BRDF factor at 2.4, set the NEAT values for the 7 bands at 0.05,0.07, 0.07, 0.05, 0.05, 0.05, and 0.12°K, set 0.5% as the systematic calibration error for all bands, and keep all other parameters as in the first example. In our simulation, NEAT is treated as a random noise. The errors in retrieved surface temperatures for total 2,000 different cases are shown in Fig. 2A. The errors in retrieved band emissivities in MODIS bands 31 and 32 are shown in Fig. 2B. The standard deviations of retrieved surface daytime and nighttime temperatures, and band-averaged emissivities in MODIS bands 31 and 32 are in ranges of 0.2-0.7°K and 0.006-0.015 over a wide range of surface temperatures in summer mid-latitude atmospheric conditions. We can see the effect of the 0.5% systematic calibration error in Fig. 2A. This makes the mean temperature error to shift to the positive direction by about 0.4°K as expected. Their histograms are shown in Fig. 3A and 3B. Note that we simulated the surface temperature variation in a very wide range as mentioned above. If we select favorable atmospheric and surface conditions and make spatial and temporal averages of the band emissivities retrieved in several clear-sky days, the band emissivities in MODIS bands 31 and 32 can be retrieved at accuracy better than 0.01 so that these retrieved emissivities can be used in the generalized split-window LST algorithm for quick retrieving LST in the same area for a period of one or more weeks depending on seasons.

In the third example for Ultisols, a kind of quartz dominated soil which is also called Red-Yellow Podzolic in soil classification system [Salisbury and D'Aria, 1992], we set the BRDF factor at 2.2, and keep the atmospheric and surface temperature parameters as in the first example. We will change NEAT and calibration error values in a series of tests, as shown in Table 3. The first column in the table indicates the test number. Seven NEAT values for 7 bands used in the new LST algorithm are listed in the second column block, and 7 calibration error values in the third column block. Standard deviations of the retrieved daytime and nighttime surface temperatures are given in the fourth and fifth columns. The standard deviations of the retrieved emissivities for MODIS bands 31 and 32 are given in the last two columns. Comparison between test 1 and test 2 indicates that the effect due to systematic calibration error 0.5% is comparable to the effect of given NEAT values. Test 3 indicates that doubling the NEAT increases the standard deviation of retrieved daytime surface temperature by 0.3 "K.

Comparing test 4 and test 5 to test 2 indicates that systematically increasing calibration error by 0.25% and 0.5% does not cause a serious problem. In test 6 through test 12, we keep the same NEAT values used in tests 1-5 except test 3 and change signs and values of the calibration errors in the 7 bands. The effects of changing signs are very significant. This means that the performance of new LST method is significantly affected by the random error in instrument calibration. In order to achieve the 1°K requirement for the LST accuracy and to retrieve band emissivities in MODIS bands 31 and 32 at the 0.01 level, the random calibration error should be smaller than 0.2%. The new LST algorithm requires consistent calibration accuracy for the 7 bands used. The split-window SST and LST algorithms also require high consistent calibration accuracy for MODIS bands 31 and 32. However, the new LST algorithm requires consistent calibration accuracy over a much wider spectral range.

5. Anticipated Future Actions

The work to establish TIR BRDF/emissivity knowledge base will be continued. Field campaigns in 1996 using the TIR instruments with concurrent overpasses by daytime and evening MAS flights have been planned to validate the new MODIS day/night LST algorithm. This new LST method will be incorporated into version 1 of the MODIS LST code.

6. Publications

1. Z. Wan and J. Dozier, A generalized split-window algorithm for retrieving land-surface temperature from space, *IEEE Trans. Geosci. Remote Sens.* accepted November 1995.

2. W. Snyder and Z. Wan, Surface temperature correction for active infrared reflectance measurements of natural materials, *Applied Optics,* in press 1996.

3. Z. Wan, W. Snyder, and J. Dozier, Retrieving and validating land-surface temperature and emissivity from EOS MODIS data, *AGU Fall ’95,* invited poster paper.

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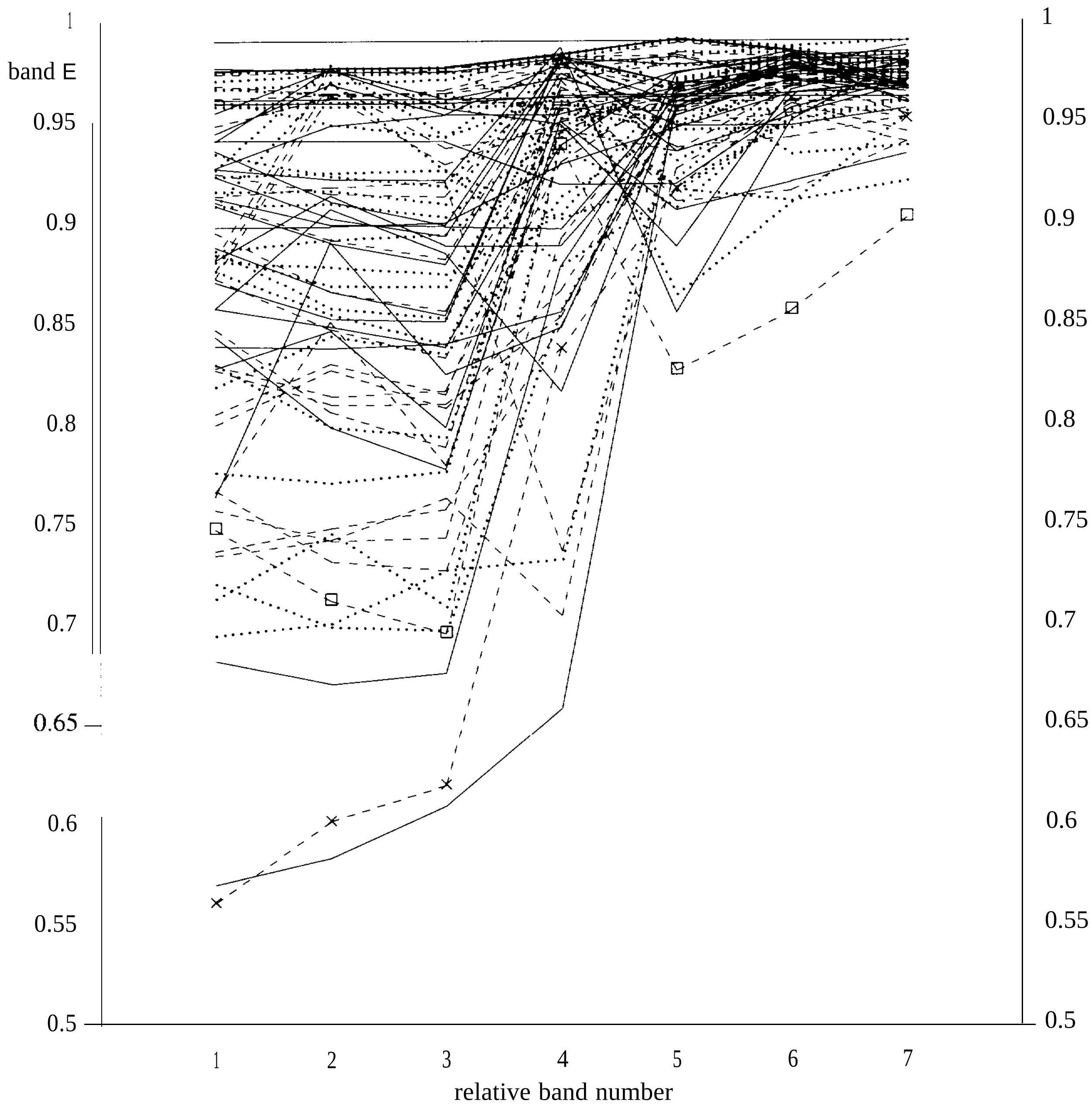

Fig. 1, Band-averaged emissivities for MODIS bands 20,22,23,29,31,32 & 33.

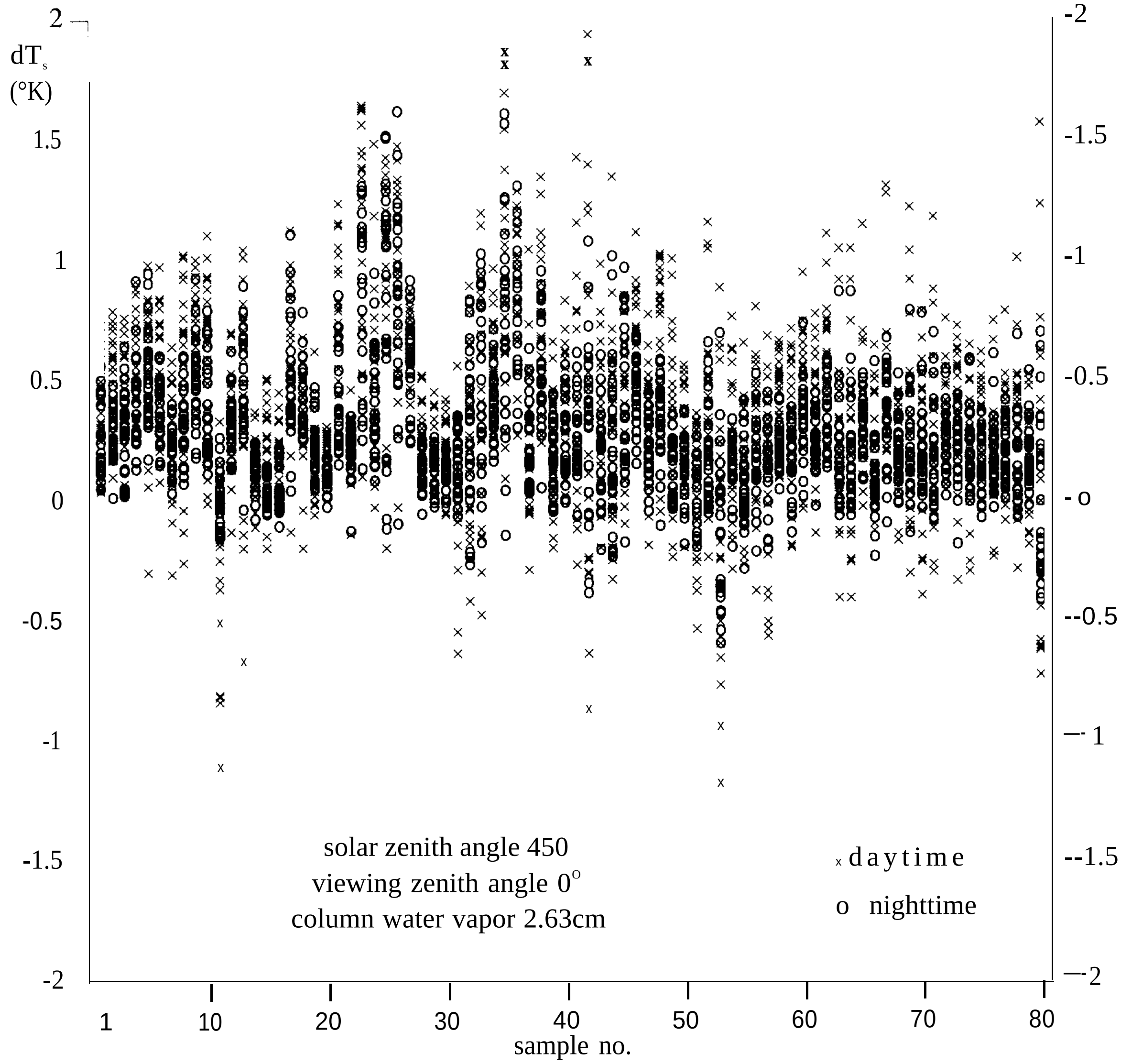

Fig. 2A, Errors in surface temperatures retrieved by the new day/night LST method.

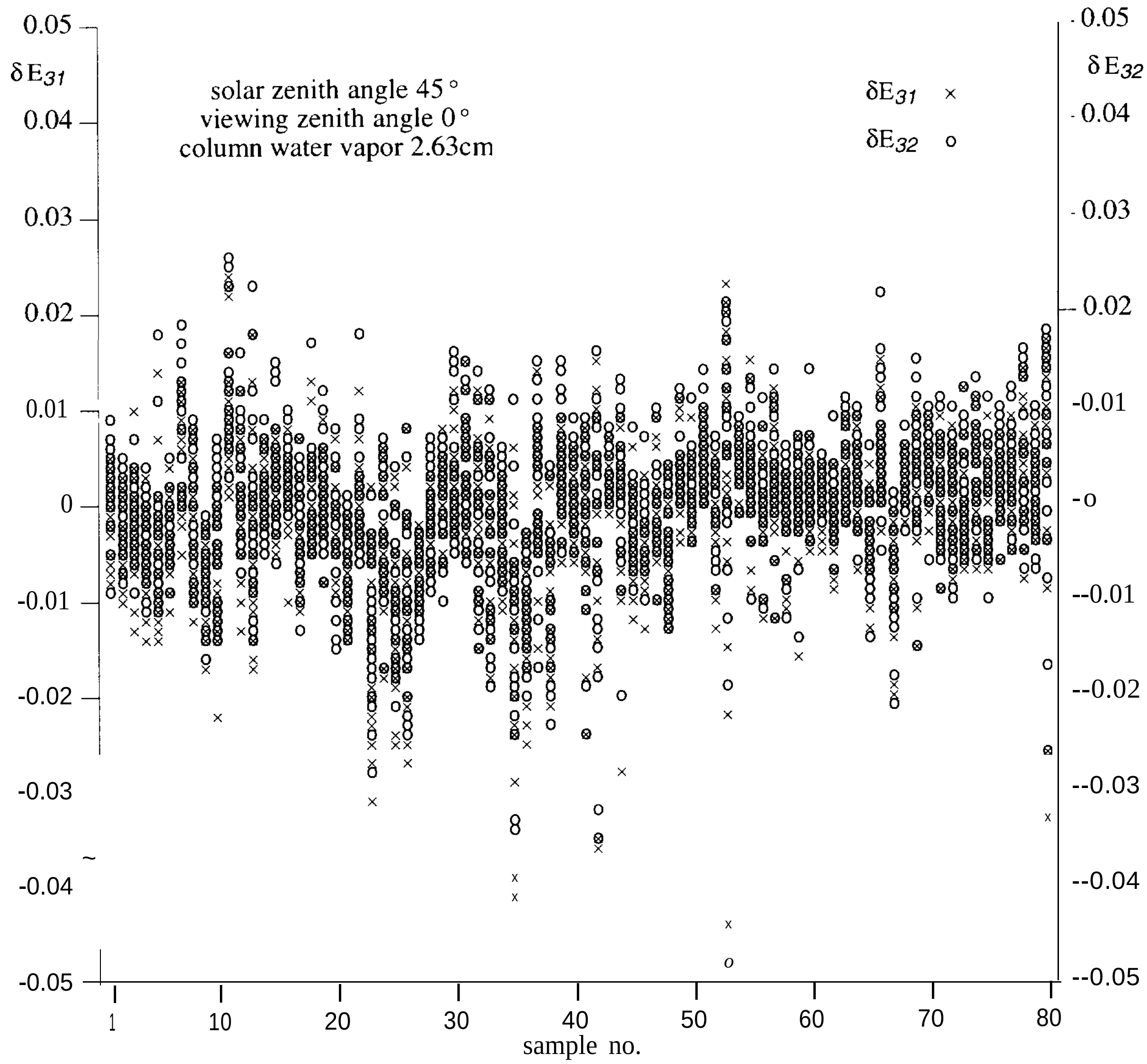

Fig. 2B, Errors in surface emissivities retrieved by the new day/night LST method.

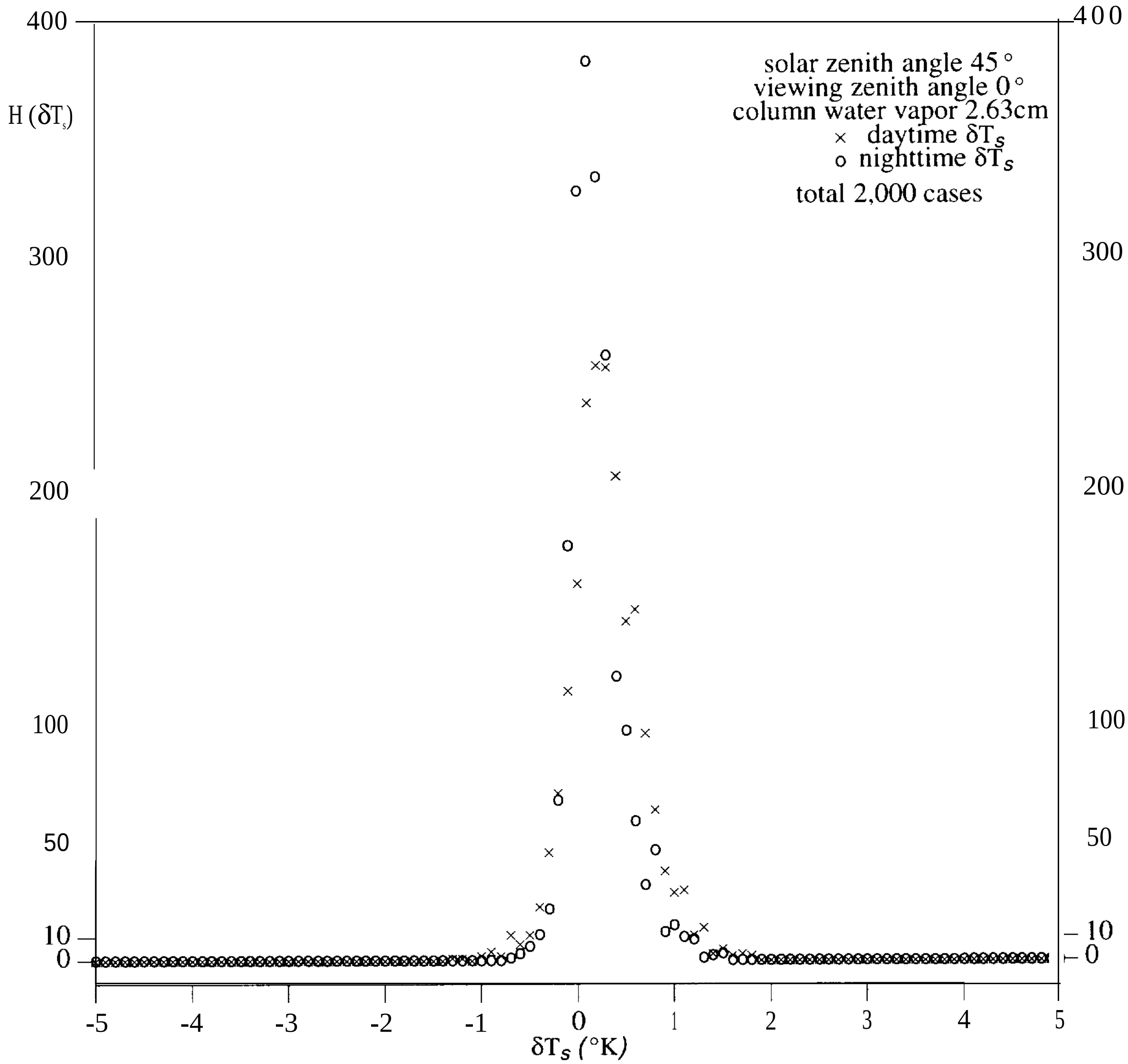

Fig. 3A, Histogram of errors in surface temperatures retrieved by the new day/night LST method.

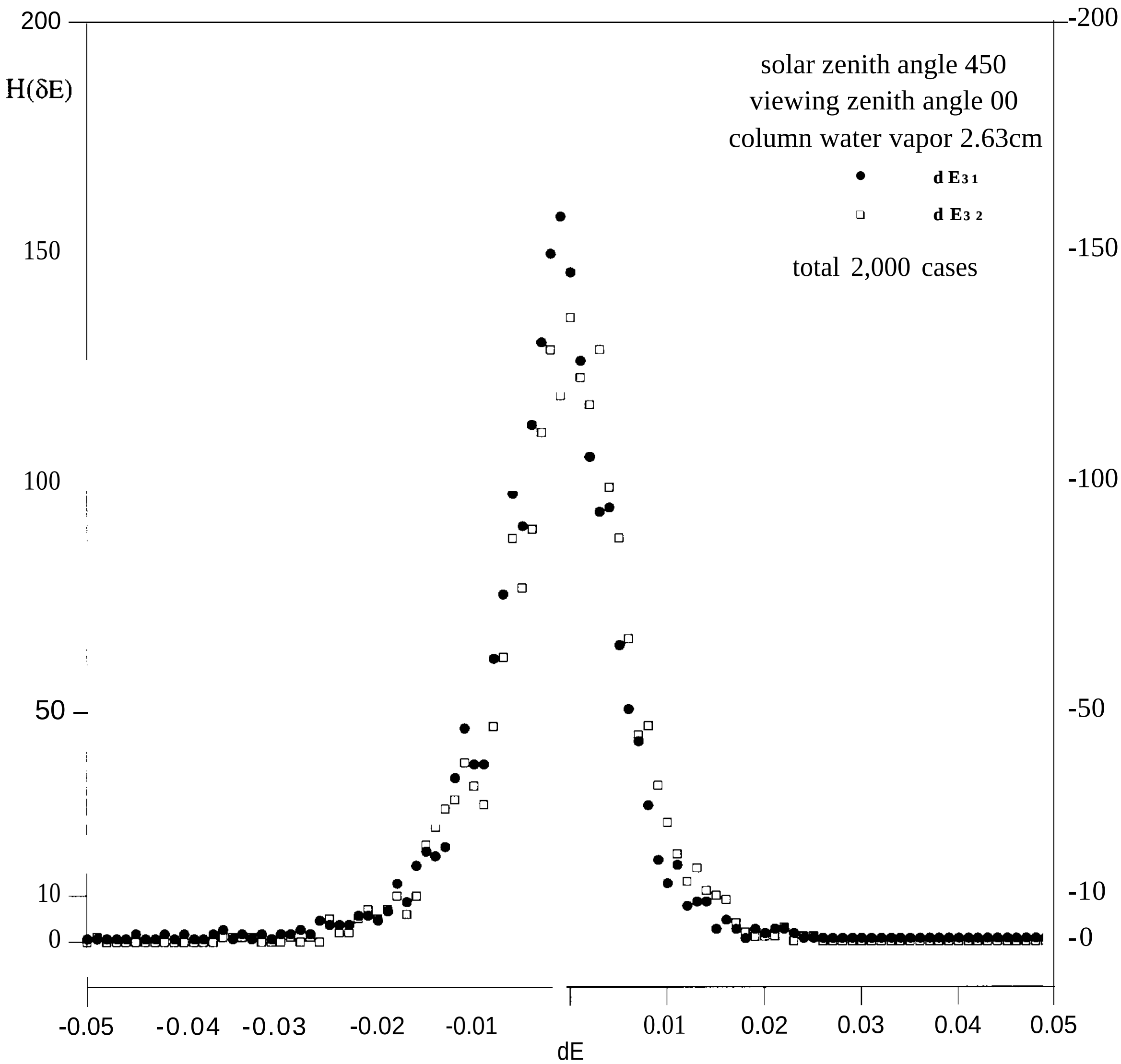

Fig. 3B, Histogram of errors in surface emissivities retrieved by the new day/night LST method.

TABLE 1. Summary of LST values over the test site (38’ 31.46’N, 115’ 42.74’W) in Railroad Valley, Nevada, during 1:22 and 1:30 PDT on 8/3/95. The size of one MAS pixel is about 50m by 50m.

size of area	mean (°C)	stdv (°C)	remarks
12 cm diameter	58.5		by radiometer
5 cm diameter	59.2		by spectrometer at θ_v 20°
1 MAS pixel	59.1		at θ_v 18.75°
3 by 3 MAS pixels	58.9	0.48	
5 by 5 MAS pixels	58.8	0.67	
7 by 7 MAS pixels	58.9	0.76	
9 by 9 MAS pixels	59.0	0.81	
11 by 11 MAS pixels	58.9	0.82	
21 by 21 MAS pixels	58.9	1.21	

TABLE 2. Specifications of the MODIS thermal infrared bands used in the new LST algorithm.

band no. in the LST algorithm	MODIS band no.	band range lower edge (µm)	band range upper edge (µm)	NEDT (°K)	Calibration Accuracy specified	Calibration Accuracy goal
1	20	3.660	3.840	0.05	1%	0.5%
2	22	3.929	3.989	0.07	1%	0.75%
3	23	4.020	4.080	0.07	1%	0.75%
4	29	8.400	8.700	0.05	1%	0.5%
5	31	10.780	11.280	0.05	1%	0.5%
6	32	11.770	12.270	0.05	1%	0.5%
7	33	13.185	13.485	0.25	1%	0.75%

TABLE 3. The dependence of standard deviations of soil (Ultisols) surface emissivities and temperature retrieved by the new LST algorithm on NEAT and calibration errors.

test no.	NEDT (°K)	calibration errors (%)	d T_{s-day} (°K)	d $T_{s-night}$ (°K)	$\delta\ \varepsilon_{31}$	$\delta\ \varepsilon_{32}$
1	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.00,0.00,0.00,0.00,0.00,0.00,0.00	0.65	0.21	0.013	0.012
2	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.50,0.50,0.50,0.50,0.50,0.50,0.50	0.69	0.26	0.012	0.012
3	0.10,0.14,0.14,0.10,0.10,0.10,0.25	0.50,0.50,0.50,0.50,0.50,0.50,0.50	0,99	0.34	0.014	0.014
4	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.75,0.75,0.75,0.75,0.75,0.75,0.75	0.69	0.30	0.012	0.012
5	0.05,0.07,0.07,0.05,0.05,0.05,0.12	1.00,1.00,1.00,1.00,1.00,1.00,1.00	0.68	0.31	0.013	0.013
6	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.20,0.20,0.20,-0.2,-0.2,-0.2,-0.2	0.82	0,22	0.017	0.018
7	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.50,0.50,0.50,-0.5,0.5,-0.5,0.5	1.07	0.71	0.017	0.012
8	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.50,0.50,0.50,-0.5,-0.5,-0.5,-0.5	1.11	0,53	0.026	0.026
9	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.75,-0.75,0.75,-0.75,0.75,-0.75,0.75	1.27	0.70	0.019	0.024
10	0.05,0.07,0.07,0.05,0.05,0.05,0.12	0.75,0.75,0.75,-0.75,-0.75,-0.75,-0.75	1.26	0.58	0.032	0.033
11	0.05,0.07,0.07,0.05,0.05,0.05,0.12	1.0,-1.0,1.0,-1.0,1.0,-1.0,1.0	1.45	0,84	0.025	0.029
12	0.05,0.07,0.07,0.05,0.05,0.05,0.12	1.0,1.0,1.0,-1.0,-1.0,-1.0,-1.0	1.32	0,60	0.035	0.037